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MODULATION-RATE PERCEPTION: IDENTIFICATION AND DISCRIMINATION OF MODULATION RATE USING A NOISE CARRIER

by

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Modulation-rate thresholds were measured for three tasks: a fixed-standard, forced-choice discrimination task with a 500-ms interstimulus interval; a random-standard, forced-choice discrimination task with an 8-sec interstimulus interval; and an identification task. Thresholds were obtained for modulation rates from 14 to 224 Hz with noise carriers band-pass filtered from 500-4000 Hz, 500-1600 Hz, 1700-2800 Hz, and 2900-4000 Hz. The four bands yielded similar results except for modulation rates of 150 Hz and greater, where th 500-1600 Hz thresholds were higher. Fixed-standard discrimination thresholds were a relatively constant 3 Hz for modulation rates up to 66 Hz. The increase of thresholds for modulation rates above 66 Hz could be due to temporal resolution limits with a time constant of about 2.4 msec. For modulation rates above 100 Hz, critical-band filtering decreases sensitivity to modulation rate for the 500-1600 Hz noise band. Resolution in the random-standard discrimination task was similar to that for the identification task. Thresholds were elevated relative to

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SUMMARY PAGE

THE PROBLEM

To evaluate the potential role of amplitude-modulation rate in identification of complex sounds and to distinguish sensory and nonsensory factors that underlie the perception of modulation rate.

THE FINDINGS

Sensory and nonsensory limitations in modulation-rate perception were identified. Results from a fixed-standard discrimination task describe the sensory limits, and results from two other tasks describe additional limitations which play a role under less optimal conditions, more typical of everyday identification of sounds. A model of intensity perception (Durlach & Braida, 1969) was extended to modulation-rate perception. The results and model contribute to an understanding of how well temporal variations in a signal can be used to distinguish complex sounds.

APPLICATION

The results will contribute to an understanding of aural classification of sonar signals.

ADMINISTRATIVE INFORMATION

This investigation was conducted under ONR Work Unit No. 61153N - RR4209.001 - ONR 4424207, "(U) Auditory classification based on the identifiability of complex stimulus features." It was submitted for review on 15 November 1988, approved for publication on 30 January 1989, and has been designated as NSMRL Report # 1128.

ABSTRACT

Modulation-rate thresholds were measured for three tasks: a fixed-standard, forced-choice discrimination task with a 500-ms interstimulus interval; a random-standard, forced-choice discrimination task with an 8-sec interstimulus interval; and an identification task. Thresholds were obtained for modulation rates from 14 to 224 Hz with noise carriers band-pass filtered from 500-4000 Hz, 500-1600 Hz, 1700-2800 Hz, and 2900-4000 Hz. The four bands yielded similar results except for modulation rates of 150 Hz and greater, where the 500-1600 Hz thresholds were higher. Fixed-standard discrimination thresholds were a relatively constant 3 Hz for modulation rates up to 66 Hz. The increase of thresholds for modulation rates above 66 Hz could be due to temporal resolution limits with a time constant of about 2.4 msec. For modulation rates above 100 Hz, critical-band filtering decreases sensitivity to modulation rate for the 500-1600 Hz noise band. Resolution in the random-standard discrimination task was similar to that for the identification task. Thresholds were elevated relative to fixed-standard thresholds except at the edges of the stimulus range. In the random-standard discrimination task, a pronounced criterion bias was present for stimuli near the edge of the range. Durlach & Braida's (1969) model describes the data well and provides quantitative measures in good agreement with those for intensity perception.

INTRODUCTION

Recent research has emphasized the importance of the amplitude envelope for recognition of complex auditory signals. For example, Van Tassel et al. (1987) argued that amplitude modulation cues in the range from 20 to 200 Hz can be used to encode phonetic features. Mackie, et al. (1981) provided evidence that some perceptual dimensions of sonar signals are related to modulation in the amplitude envelope of these signals. Our ability to enhance recognition of sonar signals and to develop classification algorithms would be greatly increased by an understanding of how human listeners derive distinctive information from a signal's envelope.

Macmillan and his colleagues (Macmillan, Braida, & Goldberg, 1987; Macmillan, 1987) suggested that the presence of auditory perceptual features may be inferred from a comparison of thresholds from a fixed-standard, forced-choice discrimination task with those from an identification task. Forced-choice discrimination thresholds reveal the ultimate resolving power of the sensory system without any constraints due to more central limitations. An identification task places additional attentional or memory constraints on the listener. A close correspondence between thresholds for these two tasks demonstrates that central auditory processing preserves the sensory information, presumably because of its importance for aural recognition of complex sounds. Other stimulus differences will not be resolved as well in an identification task as in a discrimination task, due to central-processing limitations. Durlach & Braida (1969), whose work on intensity perception formed the basis for Macmillan's research, described these more general limitations.

The present research uses the Durlach & Braida and Macmillan approach to examine the perceptual encoding of one aspect of the envelope, modulation frequency. Listeners' abilities to resolve modulation frequency was measured using a fixed-standard, forced-choice task and an identification task. Fixed-standard, forced-choice data have been collected using a tone carrier (Buus, 1983) and a noise carrier (Ahroon & Fay, 1977; Formby, 1985), but very little work has been done on identification of modulation rate. Hanna (1988) compared forced-choice discrimination thresholds with those from an identification task. For a noise carrier and modulation rates less than 50 Hz, thresholds for the two tasks are similar. However, this result may be specific to the range of stimuli in that experiment. The "edge" of the stimulus range can serve as a perceptual reference and produce good identification of stimuli near the edges of the range. by using a larger range of modulation rates, the present study determined the degree to which Hanna's identification thresholds were influenced by proximity of the edge of the stimulus range. Furthermore, the present study was intended to determine whether modulation perception can be modeled in the same way that Durlach & Braida described intensity perception. Four different stimulus frequency bands were used to determine whether modulation perception is similar for these stimuli. Previous work suggests that temporal resolution differs as a

function of spectral content and these differences may be significant for central encoding of modulation rate.

METHOD

1. Apparatus. Broadband noise was multiplied by a DC-offset sinusoid to produce essentially 100% amplitude-modulated noise (peak-to-trough ratio of 60 dB). The modulated waveform was gated on and off with a 20-ms sine-squared ramp to minimize gating transients. Total duration was 500 ms. The resulting waveform was bandpass filtered by a Wavetek Brickwall filter (Model 753A, asymptotic rejection rate of 115 dB/octave) and presented to the listeners over TDH-50P earphones at a spectrum level of 33 dB (re 20 uPa).

Table I

The modulation-rate increments, in Hz, for each of the standards used in the two discrimination tasks.

Mod. rate (Hz)	500-ms ISI Increments (Hz)	8-sec ISI Increments (Hz)
14	2,4,8,16	2,4,8,16
20	2,4,8,16	2,4,8,16
30	2,4,8,16	2,4,8,16
44	2,4,8,16	4,8,16,32
66	2,4,8,16	8,16,32,64
100	4,8,16,32	16,32,64,128
150	4,8,16,32	16,32,64,128
224	16,32,64,128	32,64,128,156

2. Procedure. A two-interval, two-alternative forced-choice procedure was used for the discrimination task. Each trial consisted of two sequential stimuli: a standard, which had a fixed modulation frequency over a block of 60 trials, and a comparison stimulus, which was increased in modulation frequency by one of four possible values (Table I) on each trial. The two were presented in random order. The subject indicated which of the two had the higher modulation rate. The interstimulus interval (ISI) was 500 ms. One of eight modulation frequencies -- 14, 20, 30, 44, 66, 100, 150, or 224 Hz -- was used as the standard across blocks. Each of the eight standards was used twice in each session, so each two-hour session consisted of sixteen 60-trial blocks. The frequency-band of the Wavetek filter was fixed for each session and was either 500-4000 Hz (broadband), 500-1600 Hz (low band), 1700-2800 Hz (middle band), or 2900-4000 Hz (high band). Three sessions of data were collected for each frequency-band.

After completion of the discrimination task, an identification task was used. On each trial, the listener heard one of nine modulation frequencies -- 14, 20, 30, 44, 66, 100, 150, 224, or 334 Hz -- and identified which of the nine had been presented. In each two-hour session, 15 blocks of 90 trials were presented, yielding 150 trials per modulation frequency per day. Each day one of the four frequency-bands from the discrimination task was used. Three sessions of data were collected for each frequency-band.

Finally, data were collected for the 500-4000 Hz band using the discrimination procedure already described but with two exceptions: a) an 8-sec interstimulus interval was used rather than a 500-msec interval, and b) the standard was not fixed across blocks but was randomized from trial to trial. Each two-hour session consisted of ten 40-trial blocks. Eight sessions of data were collected for two of the listeners, and three sessions for the third.

3. Listeners. Three women with audiometrically normal hearing (thresholds of 15 dB HTL or better) served as subjects. Two were paid for their participation; the third was a member of the scientific staff.

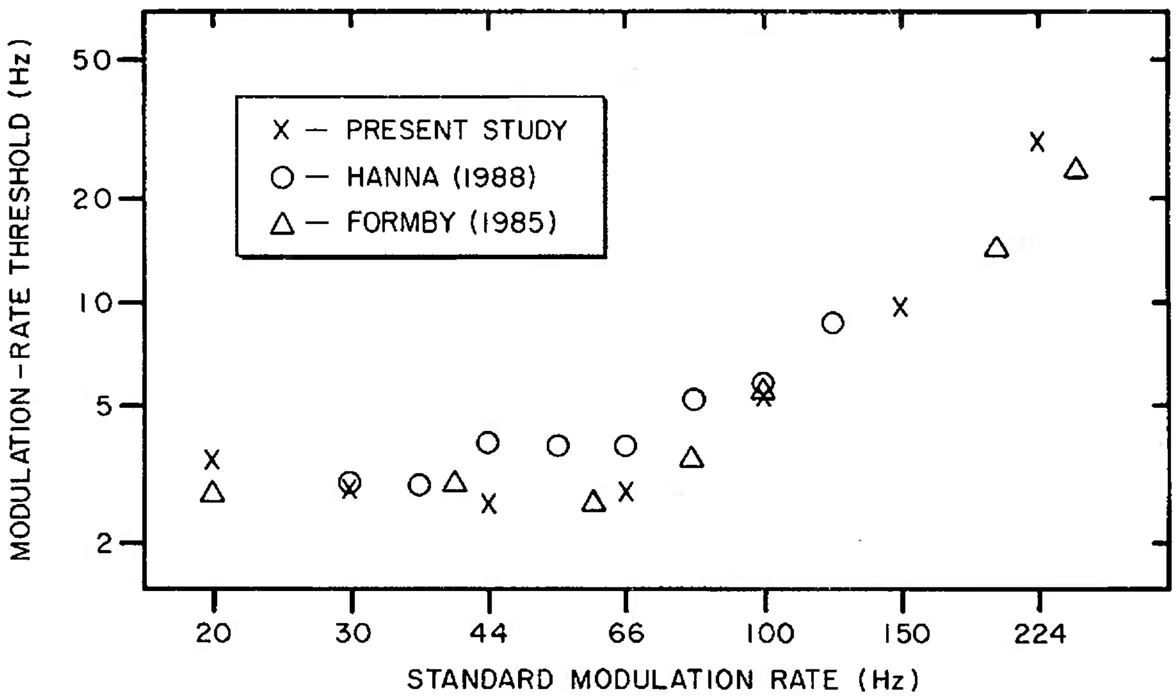

Figure 1. Modulation-rate discrimination thresholds, in Hz, as a function of modulation rate, in Hz, for the 500-4000 Hz condition (x). The results from two other studies are also shown: Hanna (1988) (o) and Formby (1985) (△).

RESULTS AND DISCUSSION

1. Discrimination task (500-ms ISI). The data were collapsed across blocks and a d' was estimated for each combination of modulation frequency and increment. The d' values for each standard were then fitted with a psychometric function of the form $d' = a(\Delta f) + b(\Delta f)^2$. The value of Δf that would yield a d' of 1 was estimated from the fitted function.

Figure 1 shows the results for the 500-4000 Hz band (crosses) along with comparable results from two other studies. Threshold values of Δf are plotted as a function of modulation frequency. The circles represent the average of two of the three subjects[1] from Hanna (1988), who used a 500-4000 Hz signal identical to that used here; the triangles are the results from Formby (1985), who used a somewhat broader band, limited by the TDH-49 earphones in that study. The agreement among the three studies is quite good. All three functions show a flat region extending from 20-66 Hz. Previous studies (Miller & Taylor, 1948; Pollack, 1952; Mowbray, Gebhard & Byham, 1956) have not shown a constant threshold value for the region 20-66 Hz, but they did not use a criterion-free measure, such as the two-alternative, forced-choice task used in the present study and in Formby's (1985). Thresholds increase for modulation rates greater than 66 Hz. The data are consistent with the work of Ahroon & Fay (1977), who showed that $\Delta f/f$ is constant for modulation rates from 50-200 Hz.

Figure 2 shows threshold values of Δf as a function of modulation frequency for each of the four frequency-bands. The functions are similar except at modulation rates of 150 and 224 Hz. Threshold values are a relatively constant 3 Hz for modulation frequencies less than or equal to 66 Hz for all four conditions. However, both the present study and Formby's show that thresholds decrease for modulation rates less than 20 Hz. For modulation rates greater than 66 Hz, thresholds start to increase, but are still relatively constant across the four conditions at a modulation rate of 100 Hz. For modulation rates greater than 100 Hz, thresholds increase more rapidly for the 500-1600 Hz band than for the other three bands.

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1 Thresholds for the third listener were three to four times higher than the two other listeners of that study and the three listeners of the present study.

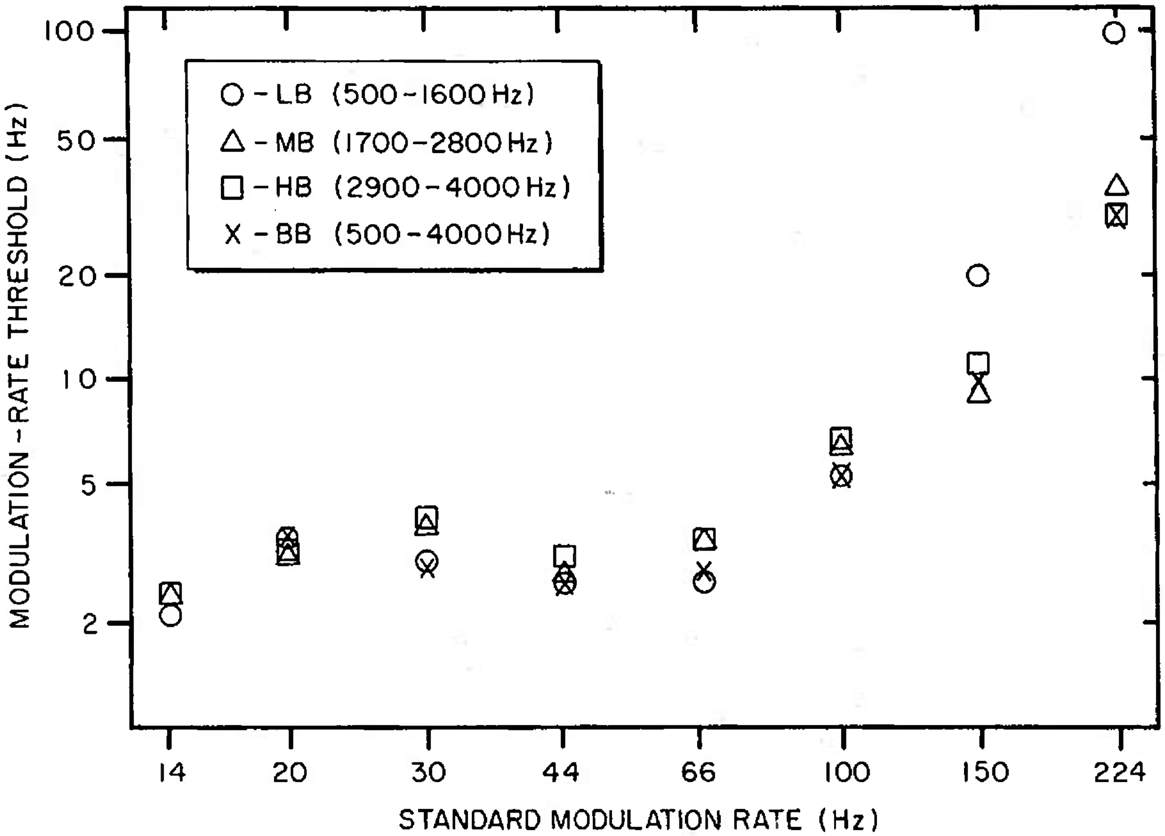

Figure 2. Modulation-rate discrimination thresholds, in Hz, as a function of modulation rate, in Hz, for the 500-4000 Hz (x), 500-1600 Hz (o), 1700-2800 Hz (▲), and 2900-4000 Hz (□).

The increase above 66 Hz may reflect limited temporal resolution within the auditory system -- this cutoff value corresponds to a time constant of about 2.4 ms and seems to be independent of spectral composition of the signal, results that are consistent with Formby's (1988). The divergence of the thresholds for the 500-1600 Hz band from those for the other frequency bands at modulation rates greater than 100 Hz presumably reflects the narrower auditory filters at lower frequencies. As modulation frequency increases, a point is reached where the components that interact to produce the modulation do not fall within a single critical band. Thus, critical band filtering can reduce the modulation within a band, making frequency discrimination more difficult. With the 100-Hz modulated noise stimulus, the intermodulation is among components spaced over a 200-Hz range. The increase of thresholds in the 100-Hz condition is consistent with a critical bandwidth of roughly 200 Hz around 1000 Hz.

It is interesting to compare the present modulation-rate thresholds using modulated noise to thresholds using two-tone complexes (Buus, 1983). The results agree in that, for each carrier frequency, thresholds are constant over a range of low modulation rates. However, for a carrier frequency of 4000 Hz, Buus's data show constant thresholds for modulation rates up to 640 Hz, whereas thresholds with modulated noise increase for rates above 66 Hz. Moreover, Buus shows thresholds that increase from 2.5 to 10.9 Hz as the carrier frequency

increases from 500 to 4000 Hz, whereas in the present study, there is only a small effect of carrier frequency -- averaged across modulation rates from 20 to 66 Hz, thresholds are 2.9, 3.3, and 3.4 Hz for the bands 500-1600 Hz, 1700-2800 Hz, and 2900-4000 Hz, respectively. Although off-frequency listening could possibly diminish any effects of carrier frequency, this explanation cannot account for differences between the two studies since the overall levels were similar (60 dB SPL for Buus and 63 dB SPL in the present study). The two stimuli differ in many respects: a difference in envelope shape, the variability of the noise carrier, and, for the two-tone complexes, the possibility of spectral or fine-structure pitch. Nonetheless, for carriers less than 2000 Hz, both studies show constant thresholds of about 3 Hz for low modulation rates.

Formby (1985) demonstrated another similarity between two frequency-discrimination tasks in the region from 20-66 Hz. He compared pure-tone frequency discrimination and noise-carrier modulation-rate discrimination. Pure-tone thresholds were 2.8 and 2.6 Hz at 40 and 60 Hz, respectively, values that are comparable to the modulation-rate thresholds and thus suggest similar limitations for the two tasks. At frequencies of 80 Hz and greater, pure-tone sensitivity is better than modulation-rate sensitivity, presumably because of the reduction of modulation depth and the use of other cues for pure-tone discrimination.

		RESPONSE	
		$\leq i$	$\geq i+1$
STIMULUS	i	(1)	(2)
	$i+1$	(3)	(4)

Figure 3. The 2 x 2 matrix used to compute <u>d'</u> for adjacent pairs of stimuli in the identification task.

2. Identification task. Consider the nine stimuli and the corresponding responses as numbered from 1 to 9. These nine stimuli can be thought of as eight pairs of adjacent stimuli. d' was calculated for each of the eight pairs as follows. A 2 x 2 matrix for the pair of stimuli i and i+1 was constructed by tabulating the responses on only those trials where either stimulus i or i+1 was presented. For each of the two stimuli, the responses were categorized as either greater than i or less than i+1. That is, the four cells of a given matrix, shown in Figure 3, were defined as: 1) a response to stimulus i of i or less, 2) a response to stimulus i of i+1 or greater, 3) a response to stimulus i+1 of i or less, and 4) a response to stimulus i+1 of i+1 or greater. For each matrix, a d' was computed by dividing the number of responses in category (1) by the number in [(1)+(2)] and treating it as a hit rate, and dividing the number of responses in category (3) by the number in [(3)+(4)] and treating it as a false alarm rate (Green & Swets, 1974). This response categorization was judged to be appropriate because no pronounced response biases were observed. Figure 4 shows d' as a function of the two modulation frequencies that determined the d'. As for the discrimination task, the four frequency-bands yield nearly identical results except for the 500-1600 Hz band at modulation rates greater than 100 Hz, where d's are lower.

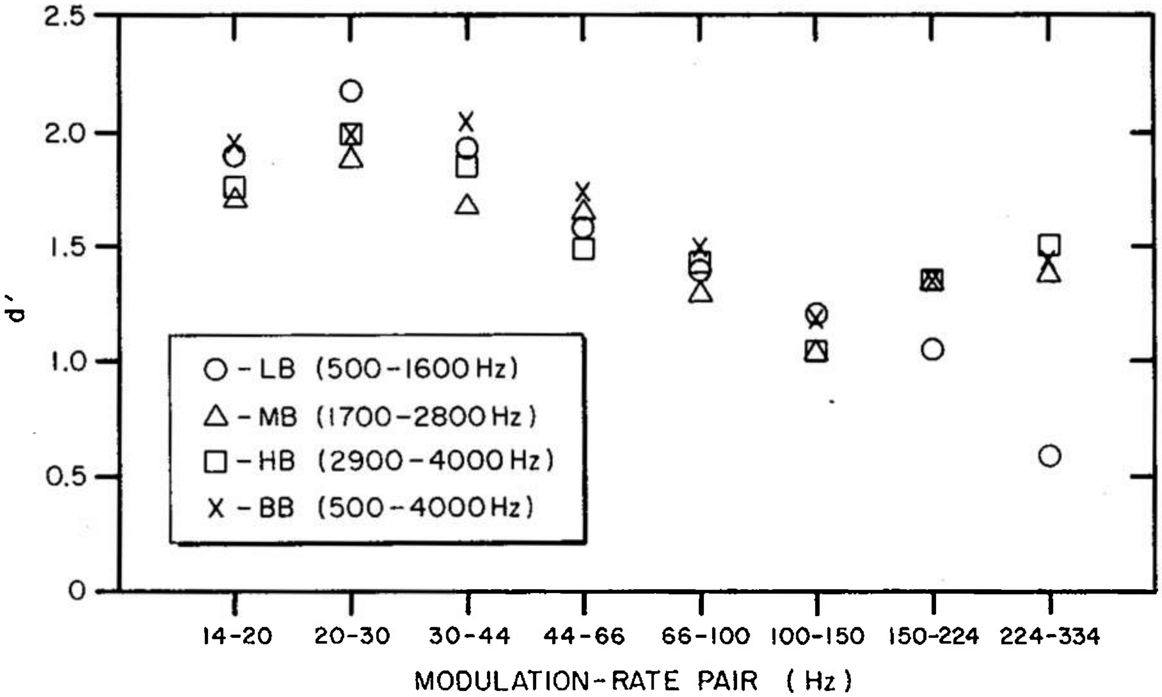

Figure 4. d' for adjacent stimuli from the identification task, as a function of the modulation rates, in Hz. The symbols correspond to the same conditions in Figure 2: 500-4000 Hz (x), 500-1600 Hz (o), 1700-2800 Hz (△), and 2900-4000 Hz (□).

The modulation difference needed for a d' of 1.0 was estimated from the d's in Figure 4. The threshold values for the 1700-2800, 2900-4000, and 500-4000 Hz bands were averaged and the results are shown in Figure 5 (triangles). The threshold values from the discrimination task for the same three bands were also averaged and are plotted (circles) for comparison. For the identification task, threshold increases roughly linearly, with threshold values approximately 30% of the modulation rate. Thresholds for the extreme modulation rates are comparable to those from the discrimination task, differing by a factor of 1.5-2.5; however, in the middle range, thresholds are markedly higher in the identification task by a factor of almost 10.

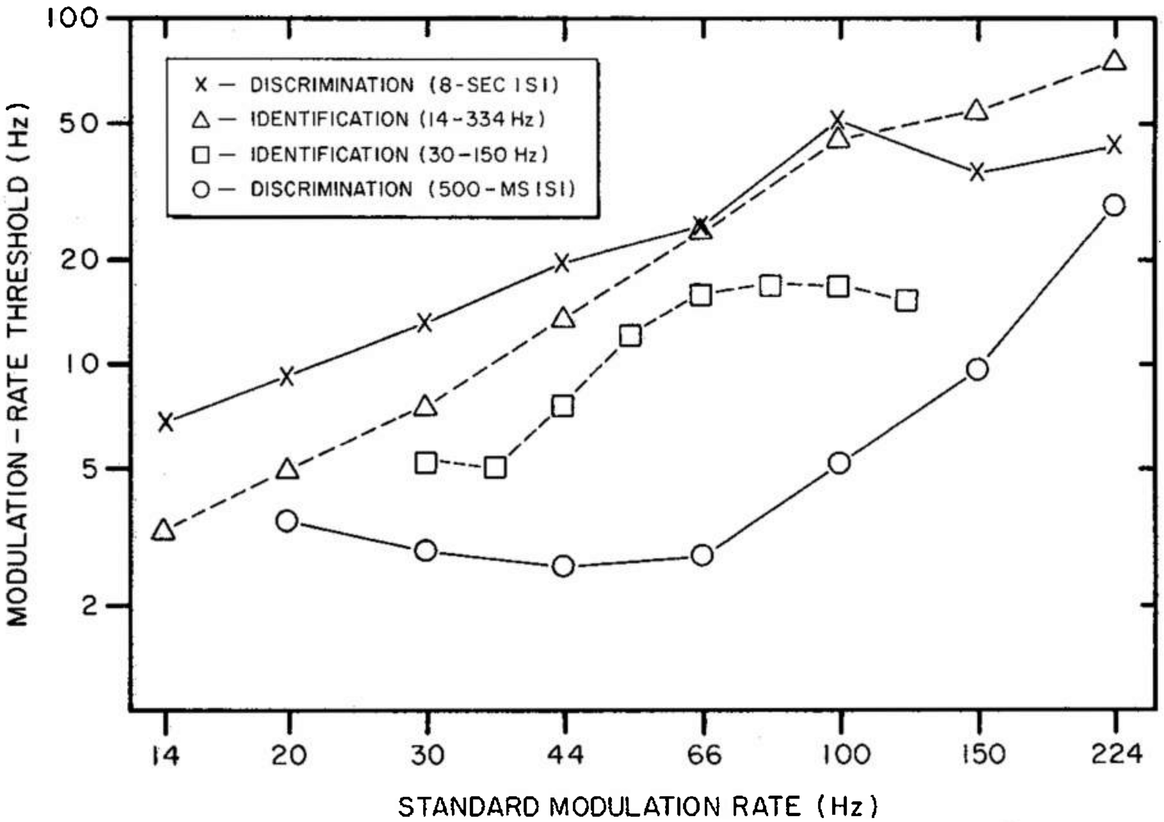

Figure 5. Modulation-rate thresholds, in Hz, as a function of modulation rate, in Hz, with a 500-4000 Hz noise carrier: the 500-ms ISI discrimination task (o), the identification task (△), the 8-sec ISI discrimination task (x), and a smaller-range identification task (Hanna, 1988) (□).

One intent of the study was to determine whether certain modulation rates are resolved as well in the identification task as in the discrimination task. Such a result would suggest that central encoding of the stimulus envelope preserves the peripheral sensory resolution of these features, indicating a potentially important role in classification of complex sounds. Hanna's (1988) results suggest that modulation frequencies less than 50 Hz may be resolved as well in an identification task as in a discrimination task. The squares in Figure 5 show the identification results from this previous study. Identification thresholds are higher for the present study's broader range. In both studies, identification thresholds are larger than discrimination thresholds except at frequencies near the extremes of the stimulus continuum. Thus, the two studies indicate no enhanced encoding of any absolute modulation rates, but only enhancement near the edges of the continuum. These "edge effects" are commonly observed in tasks of this sort (Berliner, Durlach, & Braida, 1977).

The identification results from the two studies shown in Figure 5 are similar in form. Thresholds in the broad range condition are proportionally larger than those in the narrow range condition, except as influenced by edge effects. This result is consistent with Durlach & Braida's prediction that, for large stimulus ranges, the variability of stimulus encoding is determined by the size of the stimulus range, rather than by sensory limitations. The "size" of the stimulus range can be defined as the number of just-discriminable stimuli along that continuum. If "just-discriminable" means a difference yielding a <u>d'</u> of 1 in a discrimination task, then the stimulus range size for the present study was about 40.4 as compared to a range size for the previous study of about 21.0. According to Durlach & Braida, for ranges of these sizes, the encoding variability is determined by the stimulus context. Because this variability is larger with the larger range, the cumulative <u>d'</u>s from the identification tasks should be only slightly larger for the larger range, in spite of the larger differences between adjacent stimuli. In fact, the cumulative <u>d'</u>s for the two tasks are 13.2 and 11.0, consistent with the theoretical framework developed by Durlach & Braida. As shown in Table II, the values for modulation-rate agree well with those for intensity ranges of 54 and 27 dB, estimated from Braida & Durlach (1972). The fact that the framework developed for intensity perception also applies to modulation-rate perception is noteworthy.

1. For comparison, Table III also shows the results for the 500-msec interstimulus interval, where no such bias effect is observed.

SUMMARY AND CONCLUSIONS

1) For all four frequency-bands, threshold values for modulation-rate discrimination were approximately 3 Hz for modulation rates from 20-66 Hz. Thresholds increased for modulation rates greater than 66 Hz, consistent with a time constant of about 2.4 msec. For the 500-1600 Hz band and modulation rates greater than 100 Hz, modulation-rate discrimination appears to be limited by critical band filtering. The thresholds for modulation rates from 20 to 66 Hz are comparable to those for two-tone modulation with carrier frequencies less than 2000 Hz (Buus, 1983) and for frequency discrimination of a sinusoid (Formby, 1985). However, differences between the present results and Buus's with higher carrier frequencies, particularly for higher modulation rates, merit further study.

2) The identification task indicates that no modulation rates are differentially encoded centrally to preserve specific sensory information. For the relatively large range of modulation rates used in the present study, a 30% difference in modulation rate was required for resolution. Thus, any aural classification of sounds based on modulation rate would require a difference of at least this magnitude unless other stimulus information were available.

3) The data from all three tasks (identification, fixed-standard discrimination with a 500-ms ISI, and random-standard discrimination with an 8-sec ISI) and earlier results from Hanna (1988) are very consistent with Durlach & Braida's (1969) model and results for intensity perception (Braida & Durlach, 1972; Berliner, Durlach, & Braida, 1977). Comparing intensity perception with modulation-rate perception shows that: resolution in an identification task shows a similar dependence on the size of the stimulus range, where the size of the stimulus range is the number of just-discriminable differences between the extremes of the range measured in a discrimination task; for both intensity and modulation rate, the resolution in a random-standard, 8-sec ISI discrimination task and an identification task are comparable; and edge-bias effects are observed with the 8-sec interstimulus interval as if the percept of the first stimulus shifts towards the middle of the range by an amount equal to the modulation-rate or intensity threshold. Central factors seem to act in a similar manner for both intensity and modulation rate.

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